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NEW WAYS TO OBTAIN MONOFOCONS FROM QUARTZ GLASS

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A method of obtaining monofocons from quartz glass based on the interaction of the glass with fluoride melts and solutions, specifically, cadmium fluoride melt and solutions of hydrofluoric acid, has been developed. The theoretical underpinnings for diverse variants of a method of producing monofocons from quartz-glass are examined.

Key words: quartz glass, monofocon, solution of hydrofluoric acid, cadmium fluoride melt, chemical interaction.

Focons (focal concentrators), which in their most general form can be defined as a rigid element in the form of a truncated cone, are used as focusing and collimating elements in fiber-optic, electro-optic and quantum-electronic systems, devices and setups. A focon can be hollow mirror, fiber-optic, fabricated from conical glass light guides sintered together, and glass-monolithic, i.e., practically a single glass fiber. In the latter case a focon is called a monofocon.

It is known [1, 2] that when light is transmitted from the small face of a focon to a large face (expanding light guide) the light rays are collimated, and when light is transmitted from the large face to the small face (light guide with decreasing cross section) the light rays are concentrated (focused). The degree to which light fluxes can be concentrated is determined by the ratio of the diameters of the focon faces, which enters into the expression for calculating the numerical aperture.

This shows that, in particular, the methods used to obtain focons must make it possible to attain strictly prescribed geometric dimensions, which is most difficult to accomplish when fabricating monofocons from quartz glass where only two methods can be used in practice: mechanical processing of a quartz-glass rod and pulling from a blank. The first method is labor-intensive and inefficient. It does not make it possible to obtain a small-face radius less than 0.2 nm and high reproducibility in mass production. The second method is energy-intensive, because the process occurs at high temperatures (even low-melting KU quartz glass obtained by paraphase synthesis has viscosity above $10^{5.5}$ Pa · sec at temperatures of the order of 2000°C [3]). In addition, the process is complicated by intense vaporization of the quartz glass (especially at temperatures above 1900°C), the possibility of quartz undergoing polymorphous transformations, the strong dependence of the crystallization activity on the external conditions and technological parameters, and the possibility of bubbles forming on pulling. The impossibility of obtaining a focon whose small face is already polished after pulling complicates the process of subsequent grinding and polishing and adversely affects the plane-parallelism of the end-faces of a monofocon and their perpendicularity with respect to the symmetry axis.

We have developed a method of obtaining quartz-glass monofocons based on the interaction of the focon with fluoride melts and solutions, specifically, cadmium fluoride melt and hydrofluoric acid solutions.

In working with cadmium fluoride melt, which was present during the development of a method of obtaining bulk glassy samples, it was found that the chemical activity of the melt is high with respect to quartz glass. This formed the basis for the method of obtaining monofocons from quartz glass. In the process, it was possible to obtain at the same time glass ceramic material that can be machined with a graphite-cutting tool (machining speed 5 mm/sec), or photo-

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chromic glass having the following characteristics with 2 mm thickness:

UV absorption edge, nm	320
IR absorption edge, nm	5200
Useful transmission range (≥ 50%), nm	370 – 4800
Wavelength range of induced absorption, nm	360 – 750
Optical density increment after irradiation for 30 sec	0.155
Coating rate over 24 h, %	47
Full coating rate, h	48

This method made it possible to simplify the technological process and reduce its energy-intensiveness (by lowering the temperature by at least 760°C) and to attain waste-free production (the byproducts of the process are glass ceramic, machinable with a graphite-cutting tool, or photochromic glass). Nonetheless, this method is not without drawbacks. Indeed, the temperature of the process remained very high (1240°C) and it was impossible to obtain a polished small face of the focon at the completion of the process without subsequent machining and its radius was not less than 0.2 nm.

A method which we developed for obtaining monofocons from quartz glass became the basic way to overcome the drawbacks examined above. We shall examine the theoretical principles of this method.

It is well known [4] that the chemical interaction of quartz glass with a solution of hydrofluoric acid is an exothermal reaction described by the equation

$$SiO_2 + 6HF = H_2SiF_6 + 2H_2O;$$
$$\Delta H^0_{298} = -138.3 \pm 8.4 \text{ kJ/mole}, \quad (1)$$

Here, the dependence of the thickness of the removed layer of quartz glass on the immersion time in the hydrofluoric acid solution at room temperature comprises a family of straight lines passing through the origin of coordinates. The slope angle of each straight line with respect to the abscissa depends on the concentration of the hydrofluoric acid solution and increases with the concentration. Therefore, the reaction described by Eq. (1) at constant concentration of the hydrofluoric acid follows the kinetics of first-order reactions and under the indicated conditions the following expression holds:

$$\delta = v_{\text{etch}}\,\tau, \quad (2)$$

where δ is the thickness of the removed layer of quartz glass; v_{etch} is the etching rate of the quartz glass (v_{etch} = const with constant hydrofluoric acid concentration); and, τ is the immersion time of the quartz glass in the hydrofluoric acid solution.

Then, immersing for time τ a quartz-glass rod in the form of a graduated cylinder with transverse radius R and bottom end coated with a layer protecting the cylinder from etching (the protective layer prevents etching on the side of the bottom surface of the cylinder in a direction parallel to its symmetry axis) in a solution of hydrofluoric acid with constant concentration (this condition is fixed) a quartz-glass layer with thickness δ determined by the expression (2) will be removed. In other words, a rod with transverse radius given by the following expression is obtained in the time τ on the section of the quartz-glass rod immersed in the hydrofluoric acid solutions:

$$r = R - \delta.$$

On this basis, to obtain a quartz-glass monofocon with small-face radius r the maximum time $\tau_{\max}$ for which the quartz-glass rod with transverse radius R must be immersed in the hydrofluoric acid solution is given by the expression

$$\tau_{\max} = \frac{\delta_{\max}}{v_{\text{etch}}}, \quad (3)$$

where $\delta_{\max} = R - r$ is the maximum thickness of the removed layer of quartz glass, required for obtaining a monofocon with small-face radius r. At the same time it is obvious that the maximum etching must occur only in the section corresponding to the bottom end of the quartz-glass rod. On the section of height h equal to the height of the monofocon obtained the quantity δ must decrease so that in the transverse section corresponding to the large face of the monofocon obtained (practically coincides with the surface plane of the hydrofluoric acid solution after immersion or before extraction of the quartz-glass rod in contact or out of contact with the hydrofluoric acid solution, respectively) with radius R equal to the transverse radius of the quartz-glass rod, the thickness of the removed layer of quartz glass $\delta_0 = 0$. This is the only case where a monofocon with small-face radius r and large-face radius R can be obtained.

For this reason in the process of obtaining a monofocon the surface of the hydrofluoric acid solution and the surface of the bottom face of the quartz-glass rod must move relative to one another with constant velocity v, and the symmetry axis of the quartz-glass rod and the surface of the hydrofluoric acid solution must remain strictly perpendicular to one another for the entire period of motion. Then, if in the process of obtaining a monofocon the maximum distance attainable between the bottom surface of the quartz-glass rod and the surface of the hydrofluoric acid solution equals the height h of the monofocon obtained, then

$$v = \frac{h}{\tau_{\max}} = \frac{h\,v_{\text{etch}}}{\delta_{\max}} = \frac{h\,v_{\text{etch}}}{R - r}. \quad (4)$$

Strictly speaking, the relation (4) is approximate. The point is that a practicable method consists of two stages whose sequence can be different. In one variant the surface of the hydrofluoric acid solution and the bottom end surface of the quartz-glass rod move relative to one another with constant velocity v until the two surfaces are separated by a distance h. Then the quartz-glass rod and the hydrofluoric acid solution are taken out of contact with one another with

velocity $v' = h/\Delta\tau$ in a time $\Delta\tau$. In the second variant the quartz glass rod and the hydrofluoric acid solution are taken out of contact with one another with constant velocity $v' = h/\Delta\tau$, where $\Delta\tau$ is the time required to attain the distance h between the surface of the hydrofluoric acid solution and the bottom end surface of the quartz-glass rod, after which the two surfaces move relative to one another with velocity v up to removal of contact. In both variants etching of the quartz glass occurs for time $\Delta\tau$. In addition, in the plane corresponding to the small end of the monofocon (the bottom face of the quartz-glass rod) the thickness of the removed layer of quartz glass is maximum $\Delta\delta_{max}$, and in the plane corresponding to the large end of the monofocon the thickness of the removed layer of quartz glass $\Delta\delta_0 = 0$.

On the basis of the expression (2) we have $\Delta\delta_{max} = v_{etch}\,\Delta\tau$. Then, substituting into this expression the value of $\Delta\tau$ determined in terms of v' and h we obtain

$$\Delta\delta_{max} = \frac{h\,v_{etch}}{v'}\,. \qquad (5)$$

It is obvious that $\Delta\delta_{max} \to 0$ as $v' \to \infty$, i.e., the relation (4) becomes exact in the limit. However, in reality, v' is the maximum attainable, definite, finite value, which indicates that in order to obtain monofocons with the exact radius r of the small end the relation (4) becomes

$$v = \frac{h\,v_{etch}}{R - (r + \Delta\delta_{max})}\,, \qquad (6)$$

and the approximate relation (4) gives the small-face radius of the monofocon $r - \Delta\delta_{max}$, i.e., the radius r accurate to within $\Delta\delta_{max}$.

It should be noted that there are many possible variants of the method of obtaining monofocons from quartz glass based on the theoretical calculations formulated above. In picking a variant the attainable constant velocity v' should be maximized.

Our method of obtaining monofocons from quartz glass is very economical (the process is conducted at room temperature), the results are highly reproducible (existence of a mathematical model of the process), and it is possible to obtain monofocons with a polished small face with radius less than 0.2 nm directly at the completion of the etching process. The different variants make it possible to increase the efficiency of the process and obtain at the same time monofocons with different heights.

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